

Radiation pressure detection and density estimate for 2011 MD

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ABSTRACT

We present our astrometric observations of the small near-Earth object 2011 MD ($H \sim 28.0$), obtained after its very close fly-by to Earth in June 2011. Our set of observations extends the observational arc to 73 days, and together with the published astrometry obtained around the Earth fly-by allows a direct detection of the effect of radiation pressure on the object, with a confidence of 5σ . The detection can be used to put constraints on the density of the object, pointing to either an unexpectedly low value of $\rho = 510_{-230}^{+250}$ kg/m³ (68% confidence interval) if we assume a typical probability distribution for the unknown albedo, or to an unusually high reflectivity of its surface. This may have important implications both in terms of impact hazard from small objects and in light of a possible ARRM to this target.

Subject headings: Astrometry — Minor planets, asteroids: general — Minor planets, asteroids: individual (2011 MD)

1. Introduction

The small near-Earth asteroid 2011 MD was discovered on 2011 June 22 by the Lincoln Near-Earth Asteroid Research (LINEAR) survey in New Mexico, USA (Blythe et al. 2011). Within 24 hours of discovery it was obvious that the object was going to have an extremely close approach to Earth in a few days, at about 18 700 km from the Earth's center (12 300 km from its surface, flying over the Southern hemisphere).

Around its closest approach the object's magnitude peaked at about $V = 11$, and it remained brighter than $V = 19$ for four days before and after the peak. As a result, more than 1500 individual astrometric positions were obtained and reported to the Minor Planet Center (MPC) in a period of less than 8 days. However, the object rapidly became faint while receding from Earth, and no further observations were reported after 2011 July 3, only 11 days after discovery.

Around that time we realized that the object was still fading at a reasonably slow rate of less than 0.5 magnitudes per week, and we would have

been able to observe it for at least two more months using the telescopes to which we have access on Mauna Kea. We were able to obtain astrometric positions of the object on 5 nights in August and early September 2011, therefore extending the observed arc on the object from 11 to 73 days, or about a factor of 6.5.

In this work we present these observations, together with an accurate analysis of the object's dynamics made possible by this extended observational arc. We also discuss the implications of this result on the object's physical properties.

1.1. Previous work

The case of 2011 MD shares some resemblance with other very small NEOs observed in the past. Of about 200 known small objects in this size range (diameter around or below 10 m), only a handful remained observable from the ground for more than a few days, because of their intrinsic faintness. Only some peculiar characteristic of the close approach can allow for an extended observability window, enough to characterize their dynamical behavior in good detail.

The first example of one such object was prob-

ably 2006 RH120, an even smaller NEO that was temporarily captured in Earth orbit in 2006-2007 (Bressi et al. 2008; Kwiatkowski et al. 2009). In that case, the long orbital phase allowed for 9 months of almost continuous observations from the ground. A second case was 2009 BD, that happened to have two very close approaches with Earth (and a couple of more distant but observable ones) in less than 3 years (Buzzi et al. 2009; Micheli et al. 2012). We recently presented our observational data and analysis of a third such object, 2012 LA (Hill et al. 2012; Micheli et al. 2013). All these objects, together with 2011 MD, share the property of having very Earth-like orbits, with very modest eccentricities and inclinations. As a result, they usually have very low relative orbital velocity with respect to our planet ($\Delta v < 4$ km/s), making their close encounters last unusually long. This same property also implies that these same objects are also among the easiest to fly-by or rendezvous with a spacecraft launched from Earth; together with the small size, this makes them plausible candidates for a Asteroid Robotic Retrieval Mission (ARRM) such as the one currently under study by NASA.

However, the 2011 MD case is peculiar because it had only a single and short close encounter with Earth, and it was therefore observable for a much shorter timespan. Furthermore, being discovered only around the time of close approach, only the second half of the observability window was available.

2. Methods

One of the goals of our observational campaign on 2011 MD was to obtain enough astrometric information to detect non-gravitational forces acting on the object. However, the short observational arc posed additional challenges compared with previous cases, such as that presented in Micheli et al. (2012).

The first and most obvious requirement is to obtain the highest possible signal to noise ratio during the observations, down to a magnitude of approximately $V = 24$ at the end of the observable arc. For all our observations we used the University of Hawaii 2.24 m telescope atop Mauna Kea, equipped with a Tektronix 2048 CCD camera. All our observations were unfiltered, to maximize the

SNR and improve the quality of the astrometry.

The second and equally fundamental step is to ensure that the highest possible astrometric quality is obtained from each image. We used custom software tools that are capable of performing high-precision astrometry on fields with significant trailing of the reference stars, as is the case in all our non-sidereally tracked exposures. An accurate description of the techniques used in this work can be found in Tholen et al. (2013). It is worth noting that our astrometry presented in this work is referenced to the PPMXL catalog (Roeser et al. 2010), currently believed to be among the least biased astrometric catalogs available, at least until a catalog from the Gaia mission will become available in the near future.

The choice of an appropriate catalog may be sufficient to minimize the possible astrometric biases of our own measurements. However, this work is based on the complete observed arc for 2011 MD, including more than 1500 positions from other observatories, retrieved through the Minor Planet Center archive. For these positions, we do not have control on the catalog used, and it is possible that catalog biases are reflected in the astrometry. To minimize this effect we used a zone-specific debiasing following Chesley et al. (2010), and applied the appropriate corrections to each coordinate before using the astrometry in our dynamical analysis.

A further important detail of a high-precision astrometric analysis is the use of an appropriate weighting procedure, based on the knowledge of an error bar associated with each astrometric position. For our observations, a formally computed error bar is available as an output of our astrometry software, computed under the assumptions explained in Tholen et al. (2013). The error components from the astrometric solution and centroiding accuracy are directly estimated by the software, while the contribution from an unmodeled catalog bias has been conservatively estimated at $0.05''$ for this analysis. Unfortunately, positions from other sources outside our control usually don't have this information. In our analysis these missing error bars were replaced with the station-specific error values used by the NEODyS web-

site¹, which are known to be conservative in most cases because of a safety factor introduced to take into account unmodeled correlations; for the sake of a conservative analysis, we decided to maintain this safety factor in our work.

It is important to point out here that the 2011 MD dataset has an additional complication: a few stations reported an extremely high number of astrometric observations in a single night. For example, the Barred Owl Observatory (IAU code I27) reported 968 positions to the MPC on the single night of 2011 June 27. Many other stations reported more than 10 positions on at least one night. These large sets of observations are extremely dangerous for a dynamical analysis, because any error source or bias specific to that station will dominate the global dataset, introducing correlations in the raw data that cannot easily be accounted for. This is especially true for a fast-moving object as 2011 MD, where even a small clock error can cause a systematic residual in all positions reported from a station. To prevent this effect we decided to down-weight every observatory that reported $N > 4$ observation in a single night². The new weight is computed multiplying the station-specific error bar discussed above by a factor of $\sqrt{N/4}$. As a result, if a set of positions from a single station in a single night contains more than 4 observations, its total weight in the final orbital solution is the same as if they reported only 4 positions. Using this approach we avoid the arbitrary rejection of some datapoints, while at the same time keeping the dataset mostly free from station-specific biases.

One final very important step is necessary to ensure that our astrometric dataset is cleaned of any possible source of systematic errors. We need to reject possible outliers, with the use a deterministic and statistically solid algorithm. In this work we use again our implementation of the Peirce criterion (Peirce 1852), as presented in Micheli et al. (2012). In this case the Peirce criterion is more appropriate than the widely use Chauvenet criterion (Chauvenet 1863), because the dataset is very large and we need to reject more than one

data point.

3. Analysis

The orbital analysis was performed on all 1536 measurements reported to the MPC, plus 16 positions obtained from our 5 nights of Mauna Kea observations (see Table 1). We first identified the reference star catalog associated with each entry, applied the debiasing corrections as in Chesley et al. (2010), and associated weights to each position with the approach described above.

We used the orbital computation software Find_Orb³ to compute a preliminary orbital solution, including all available observations, each weighted with its assigned error bar. Since the object is small, we took into account the possible effect of solar radiation pressure on the object, by allowing for an additional acceleration term in the radial direction. This dependence is parameterized with a single additional “orbital” element, the ratio between the average cross-sectional area of the object and its mass (A/m). It is important to point out here that the formal relation between the object’s cross section and the corresponding radiation pressure acceleration actually involves a term dependent on the albedo (since each photon reflected by the asteroid surface transmits twice the momentum of an absorbed one); however, since the goal of the current section is only to parameterize the effect of radiation pressure on the orbit, we will here define the A/m ratio as the one we would measure in the case of a perfect absorber, with zero albedo. The interplay of the albedo with the real cross section of the object will then be taken into account in the next section, when the A/m will be used to estimate the physical properties of the object.

In addition to the effect of radiation pressure, it is also important to point out that 2011 MD came so close to our planet that higher-order multipole gravitational terms could be relevant. In this specific case the J_2 term turns out to be the dominant non-Newtonian term, a couple of orders of magnitude stronger than the radiation pressure effect. The software Find_Orb is capable of dealing with J_2 , and it was included in our calculation.

¹newton.dm.unipi.it/~{neodys2}/mpcobs/2011MD.rwo

²The choice of 4 observations is based in part on the MPC rules, that discourage collecting “many more than three observations per objects [*sic*] per night” (quoted from www.minorplanetcenter.net/iau/info/Astrometry.html).

³www.projectpluto.com/find_orb.htm

TABLE 1
ASTROMETRY

Date [UT]	α (J2000) [hh mm ss.sss]	δ (J2000) [\pm dd mm ss.ss]	R	$\Delta\alpha_a$ [$''$]	$\Delta\delta_a$ [$''$]	$\Delta\alpha_c$ [$''$]	$\Delta\delta_c$ [$''$]
2011-08-01.413487	22 39 43.235	+56 40 34.66	22.7	0.008	0.008	0.088	0.097
2011-08-01.421289	22 39 41.662	+56 40 39.46	22.5	0.008	0.007	0.044	0.066
2011-08-01.430332	22 39 39.815	+56 40 44.48	22.3	0.007	0.007	0.061	0.061
2011-08-03.470563	22 38 21.505	+56 33 07.30	22.3	0.006	0.006	0.035	0.026
2011-08-03.474358	22 38 20.662	+56 33 07.54	22.4	0.006	0.006	0.026	0.026
2011-08-03.478086	22 38 19.833	+56 33 07.55	22.3	0.006	0.006	0.035	0.035
2011-08-03.486817	22 38 17.864	+56 33 07.12	22.4	0.006	0.006	0.097	0.092
2011-08-03.490571	22 38 17.020	+56 33 06.76	23.0	0.006	0.006	0.026	0.040
2011-08-03.494294	22 38 16.172	+56 33 06.28	22.4	0.006	0.006	0.044	0.044
2011-08-03.497970	22 38 15.337	+56 33 05.77	23.0	0.007	0.006	0.079	0.061
2011-08-07.534784	22 35 50.644	+56 10 29.80	22.5	0.007	0.006	0.083	0.053
2011-08-07.541449	22 35 49.300	+56 10 25.06	22.6	0.007	0.006	0.097	0.110
2011-08-07.548431	22 35 47.889	+56 10 19.79	22.7	0.007	0.006	0.092	0.101
2011-08-29.409194	22 23 48.426	+51 35 39.03	23.2	0.008	0.007	0.035	0.035
2011-08-29.417413	22 23 47.202	+51 35 29.45	23.1	0.008	0.008	0.048	0.048
2011-09-03.520191	22 21 17.166	+49 38 16.08	23.0	0.007	0.008	0.140	0.110

NOTE.—Astrometry, photometry and computed components of the error bar (from the astrometric solution and object centroid) for our observations of 2011 MD, referred to the PPMXL catalog. In addition to these error estimates, a catalog bias of $0.05''$ was applied to each observation during our analysis.

The next strongest term (J_3) is already much less important, because of the steeper radial dependency; the integrated acceleration caused by the J_3 multipole during the observed arc turns out to be 3 orders of magnitude less than J_2 , and about 30 times less than the radiation pressure effect⁴.

From this preliminary solution astrometric residuals were obtained. These residuals, together with each error bar, formed the basis for our rejection process, based on the Peirce criterion. For a description of the algorithm, and how it is applied to astrometric residuals (that are Rayleigh-distributed quantities) we refer the reader to the appendix of Micheli et al. (2012). The algorithm rejected 144 positions, out of a total set of 1543. Most of the rejections (96 positions) came from the single station I27 (Barred Owl Observatory), and they would have dominated the solutions if not properly rejected and deweighted.

After the rejections, we re-computed a full orbital solution, including again the effects of J_2 and radiation pressure. This solution corresponds to

a statistically significant detection of solar radiation pressure acting on the object. The best-fit value for A/m is $0.32 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$, comparable with the value presented in Micheli et al. (2012) for 2009 BD, an object of similar size.

We then computed an error bar for this value by creating Monte Carlo samples of the outlier-rejected observation set, with the addition of Gaussian noise proportional to the error bar of each observation. Our resulting 1σ estimate is $A/m = (0.32 \pm 0.06) \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$, corresponding to a 5σ detection of a non-zero value.

4. Discussion

The A/m value reported above can be used to extract useful physical information on the object. It is important to point out that 2011 MD is in an extremely Earth-like orbit, with low Δv with respect to our planet. It is also a small object, with $H \sim 28$, corresponding to a diameter of a few meters (depending on the albedo). It is therefore tempting to assume that it might not be a natural object, but rather a piece of debris of man-made origin (such as an upper stage of a rocket)

To prove beyond doubt the natural nature of 2011 MD it is possible to use the A/m value to

⁴The close approach of 2011 MD was so fast that the effective time of action of these multipole terms is tiny compared to the total observed arc, being of the order of 10^3 s.

put constraints on the density of the object. This can be done only under a series of assumptions, that will result in a correspondingly larger error bar in the density estimate.

The first and most relevant assumption is about the albedo. Unfortunately no direct or indirect estimate of the albedo is available for 2011 MD, since no thermal data were obtained during the fly-by. No color information is also available, making it impossible to restrict the range of likely values based on its spectral class. We are therefore forced to assume the broadest possible distribution for this parameter, and convolve it with the other measured quantities to compute an appropriate error bar for our density estimate. We choose to assume a probability distribution for the albedo based on data from WISE (Masiero et al. 2011).

The second value we need for a density estimate is an accurate absolute magnitude for the object, that combined with the albedo will give us an estimate of the size. Again, no well-calibrated photometry is available for 2011 MD, but we can provide an estimate based on the photometry values reported to the MPC together with the astrometric positions⁵. The nominal absolute magnitude is around $H = 28.0$, corresponding to an approximate size of about 10 m assuming a typical NEO albedo of 12%. To attach an error bar to this value we need to take into account both the statistical error of the determination and the rotational variability of the object. The second is the dominant factor in this case; useful information on the amplitude can be obtained from various sources, including the set of 968 observations reported by station I27 and already discussed for their astrometric relevance, or various analyses published online⁶. From them it is possible to

extract a time interval between consecutive minima of ~ 697 s, with a peak to peak amplitude of about 0.85 magnitudes. However, these estimates were obtained at a high phase angle ($\alpha \sim 60^\circ$), and they are not representative of the true zero-phase lightcurve of 2011 MD. We can empirically correct the observed amplitude to a zero-phase amplitude using the approach of Zappala et al. (1990), obtaining a full amplitude of ~ 0.45 magnitudes⁷. To maintain our conservative approach, we are therefore assuming an error bar of ± 0.3 on our H value, which includes both the uncertainty in magnitude and in the actual shape of 2011 MD.

Under these assumptions, it is possible to estimate the probability distribution for the density of our object, convolving the distributions of A/m , the albedo and the absolute magnitude, and following the relations derived by Vokrouhlický & Milani (2000) for the assumption of a spherical Lambertian reflector. The result is shown in Fig. 1; it is immediately evident that the average value is very low, well below water density. In particular, we obtain an average bulk density of $\rho = 510$ kg/m³, with a 1σ range (intended here as 68% of the distribution) that extends from 290 kg/m³ to 770 kg/m³.

This value, while surprisingly low, is in good agreement with the estimates presented by Micheli et al. (2012, 2013) for 2009 BD and 2012 LA, two other objects of similar size, and analyzed under similar assumptions. This peculiar behavior seem to point to either a general low bulk density (and likely very high porosity) of these small objects, or an anomalously high albedo, which need to be assumed at the level of $p_V \sim 0.6$ or more to be compatible with typical densities of even the lightest major asteroidal bodies like (253) Mathilde (Veverka et al. 1999), which are instead known to be extremely dark.

Both these interpretations, if confirmed, can have significant implications on the estimate of hazard from impact of very small bodies, which actually represent the most likely population of impactors, at least on the short term. Further-

⁵Most astrometric catalogs are not designed to provide a reliable photometric reference, and their magnitude values are provided mostly for identification purposes. As a result, magnitudes derived in reference to any of these catalogs cannot be considered calibrated photometry, since they may show random errors in excess of a few tenths of a magnitude (Monet et al. 2003), as well as large regional systematic errors. These photometric estimates can be used to extract meaningful information only in a statistical sense, averaging values obtained in different parts of the sky and possibly referred to different (and independent) catalogs.

⁶An example of a folded high-SNR lightcurve obtained around close approach is available at www.nmt.edu/~bryan/research/work/mro_images/k11m00d.

⁷The phase factors listed by Zappala et al. (1990) are dependent on the asteroid spectral type. To follow the most conservative approach we used the conversion factor for M-type asteroids, which corresponds to the largest zero-phase amplitude.

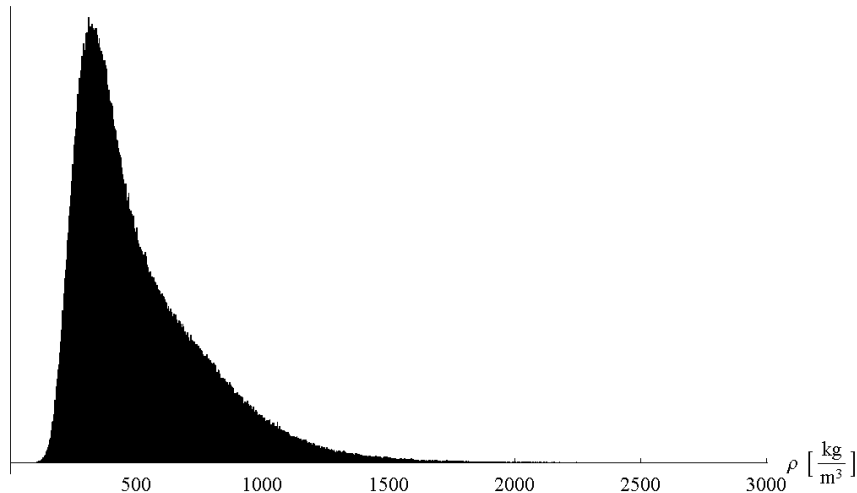


Fig. 1.— Probability distribution (with arbitrary normalization) of the density for 2011 MD

more, since 2011 MD is currently considered a prime target for a possible ARRM, a proper characterization of its physical nature (especially size and mass) is essential for the definition of an appropriate mission profile to the object.

It is also important to point out that the nominal density value we obtained, while low, is still well above the expected bulk density for man-made objects. A typical upper stage of a rocket, while being mostly made of metal, is generally a hollow cylindrical shell, and its bulk density is typically between 20 kg/m^3 to 50 kg/m^3 , about an order of magnitude less than our estimate. We can therefore at least exclude the artificial nature of the target, an important information in case an ARRM mission plans to reach and retrieve it for further study.

5. Conclusions

From the observational data presented above we obtained a statistically significant detection of the action of radiation pressure on the small object 2011 MD, based on a relatively short observational arc (only 73 days). To our knowledge this is the first detection of a non-gravitational effect on a natural object observed during a single close encounter with our planet, and shows the value of high-precision astrometry and of a proper statistical treatment of astrometric data. It is worth

noting that the data used in this work are only optical, without any radar detection.

The most relevant scientific result of this work is the low density value $\rho = 510^{+250}_{-230} \text{ kg/m}^3$ obtained for 2011 MD under assumptions of a typical albedo probability distribution. While well above typical bulk densities of man-made objects, it still unexpectedly low for a natural object, and would imply either an extremely high bulk porosity, or an estimate biased by an unusually high albedo, and therefore a significantly smaller diameter. Both these interpretations can have significant implications in terms of impact hazard from small objects, but also in light of a possible ARRM to this target or to others with comparable properties.

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Facilities: UH:2.2m.

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